How the Tevatron was Aligned

1980-83

C. Thornton Murphy

transparencies of a lecture
delivered at CERN, May, 1986
(later at Beijing and Fermilab)
1987 1993!

– notes (many!) have been added to this printed edition
which were verbal in the presentation

24 June 1986
CTM
CERN
SEMINAR

How the Tevatron was Aligned

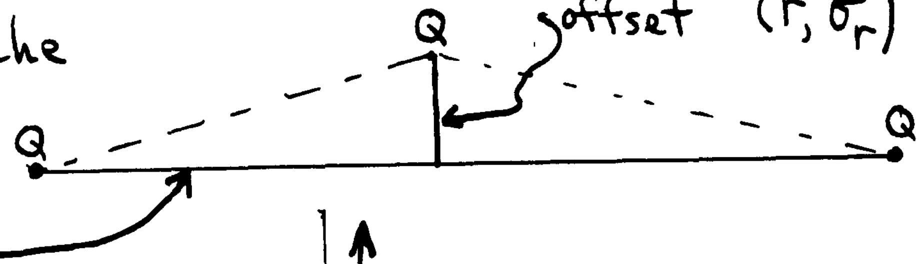
"A machine that worked despite primative survey techniques"

L. Michelotti, C. Moore, C.T. Murphy ("3M")

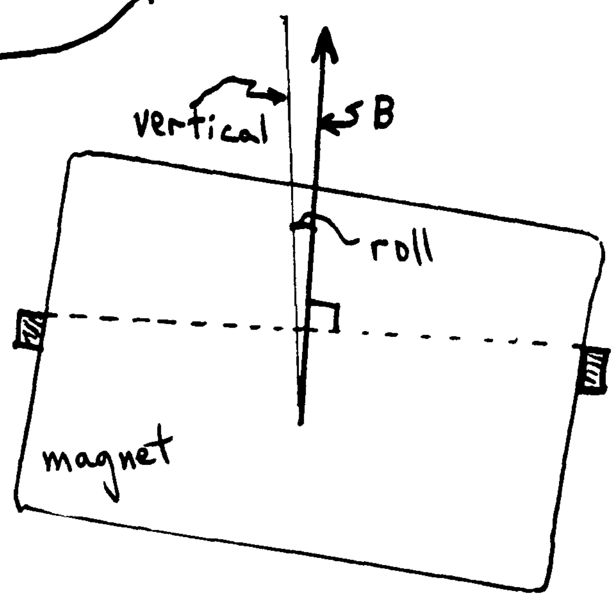
Terminology

elevation = altitude (z, σ_z)

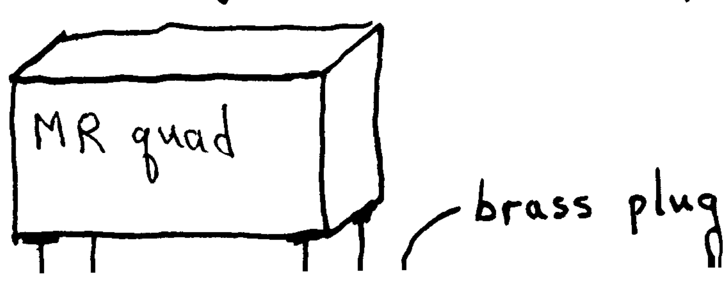
offset
Sagitta } = flèche



roll



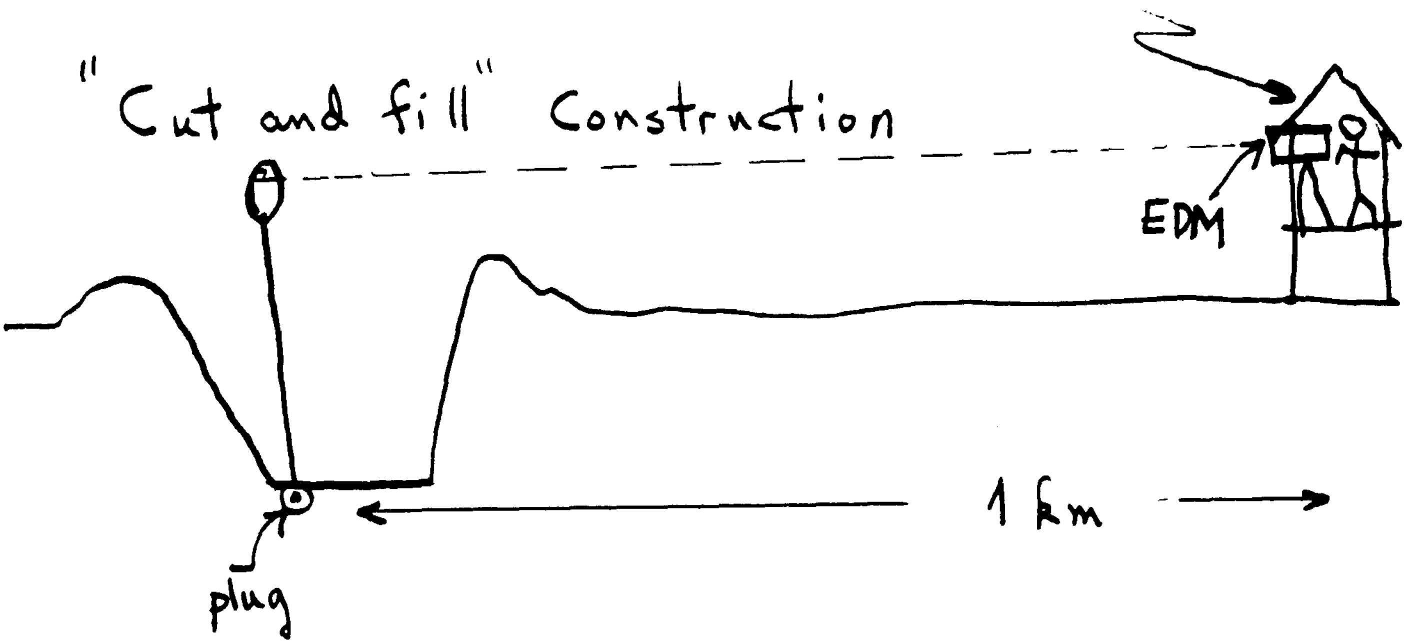
"DUSAF plugs" = original monument system:



Prehistory: Tunnel Construction + 400 GeV "Main Ring"

ca. 1971-2 Tom Collins —

"Cut and fill" Construction



— "Dusaf plug" system set, one at each quadrupole using 1-wavelength EDM ("Géodolite") from center of ring

— (then lay vault + back fill)

— accuracy said to be ± 3 mm

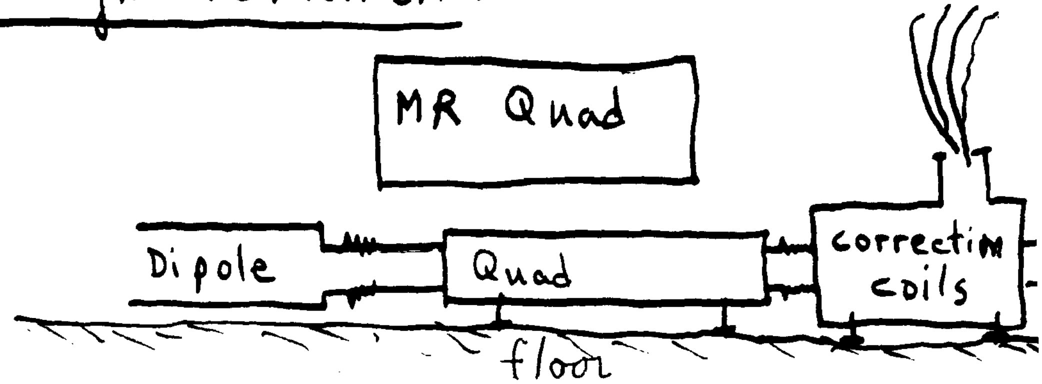
— Align quads to Dusaf plugs under terrible conditions: $-10° < T < 25°C$

Dark Ages 1972-80

- No "smoothing" allowed!
- Quads moved often per harmonic analysis of closed orbit

1980 How align Tevatron?

What is Tevatron?



- Superconducting (4,5 Tesla) 1000 GeV ring under old MR
- not wise to plan on moving quads after "cold"

Use Dusaf plugs? NO!

$\sigma_r \simeq 3$ mm ?

$\Delta r_{max} = 6$ mm (observed)

$\Delta \ell_{max}$ (along beam) = 12 mm

plugs covered by Tevatron quad

Decision: "smooth" MR quads

(- but don't actually move them)

Z: MR quad = "monument" - a mistake!

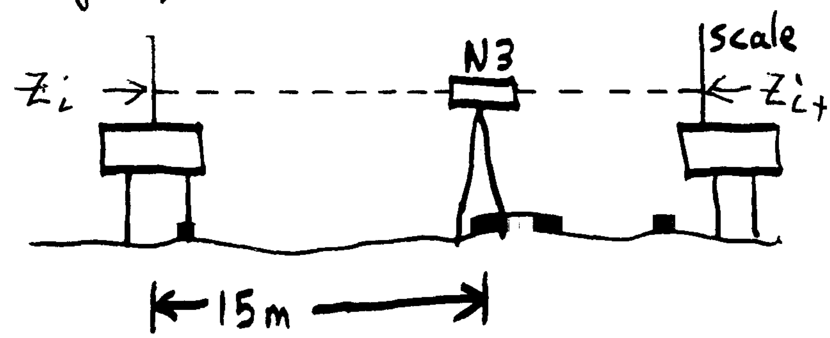
Tevatron $quad_i$ = MR $quad_i$ - $25\frac{1}{2}$" ± $(correction)_i$

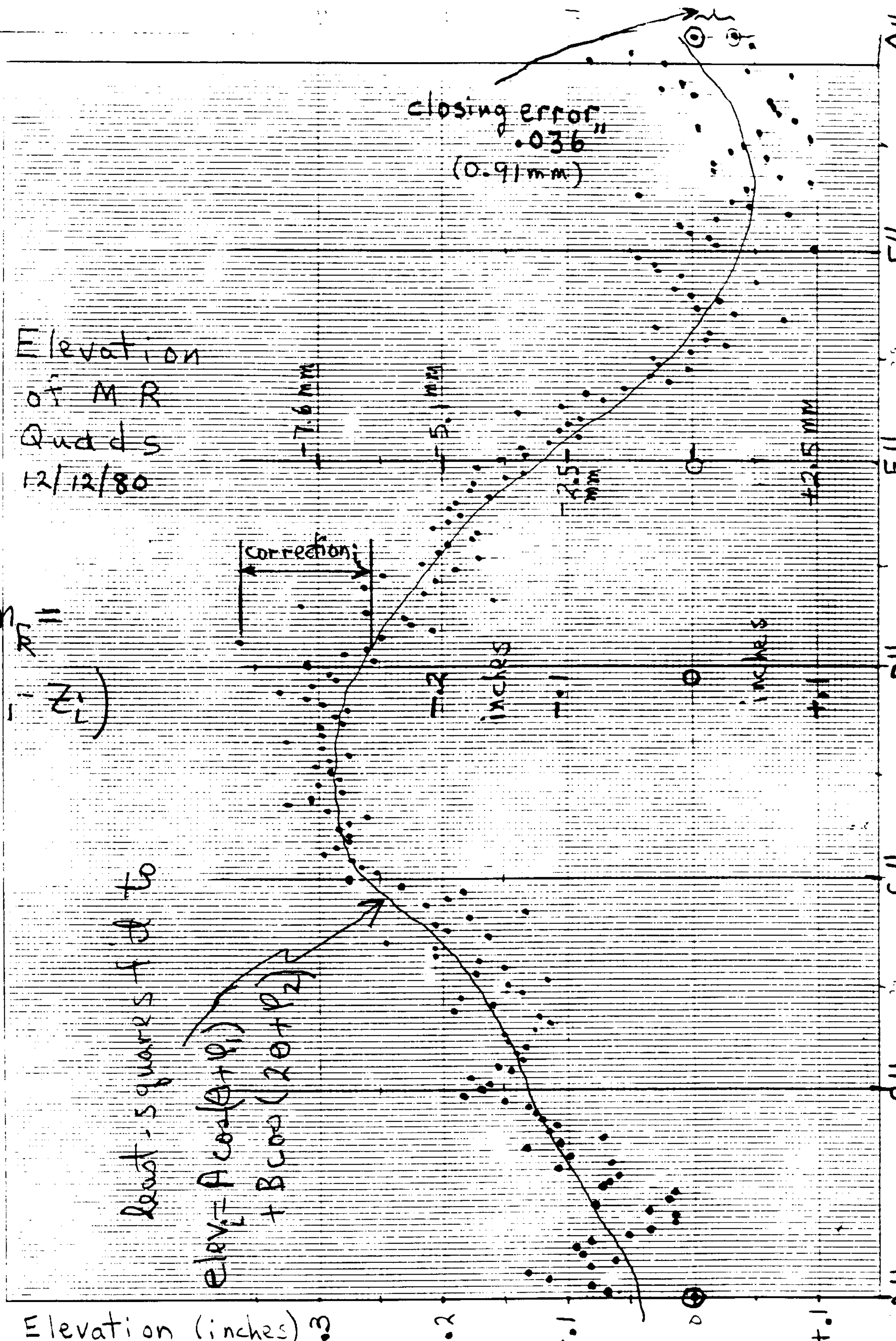
see fig

r, ℓ : install new "plug system", smoothed

Vertical

Wild N3





$$\text{elevation}_k = \sum_{i=0}^{k} (z_{i+1} - z_i)$$

~~3~~r : offsets and ∡s : Kerns DKM2 $\sigma_r = 0{,}38$ mm

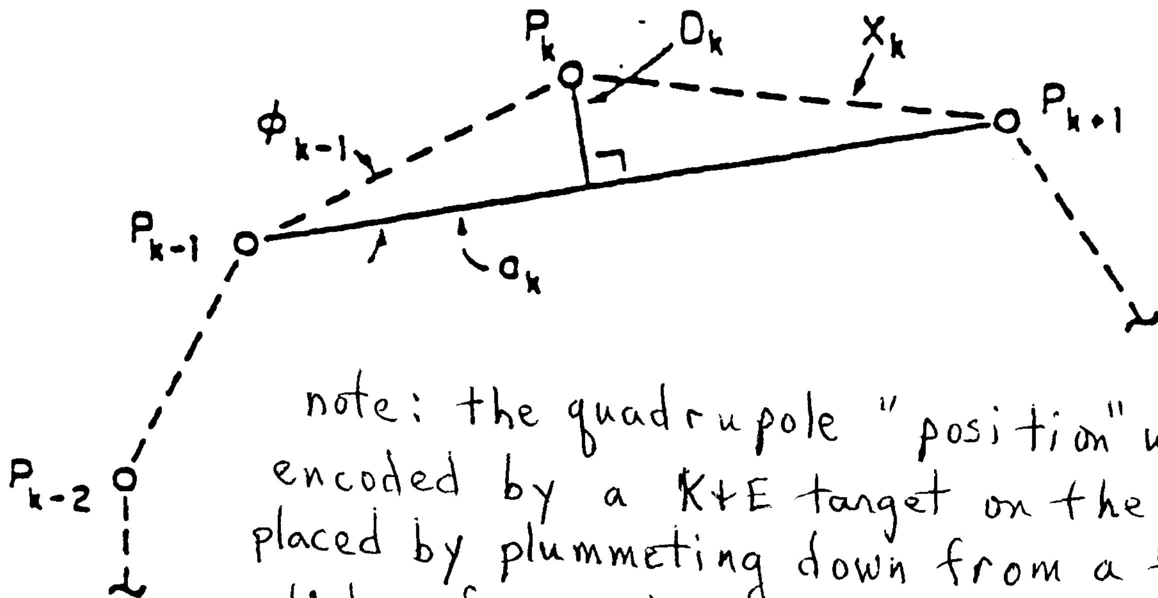
ℓ : temperature compensated steel tapes

$\sigma_\ell \simeq 1{,}8$ mm

calibrations!

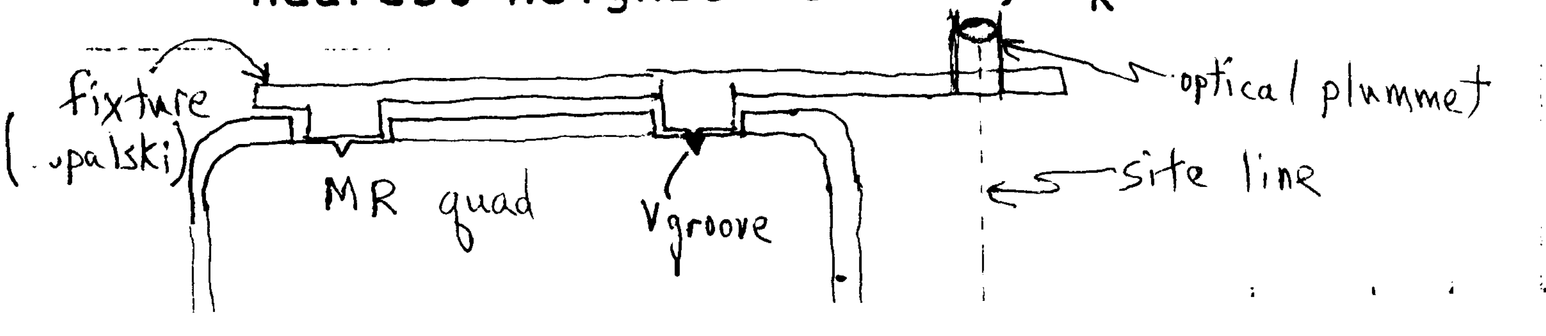
redundancy!

measured sagitta (D_K) + legs (X_K, a_x) and angles (Φ_K) of every triangle in ring.
Measured each sagitta <u>twice</u>

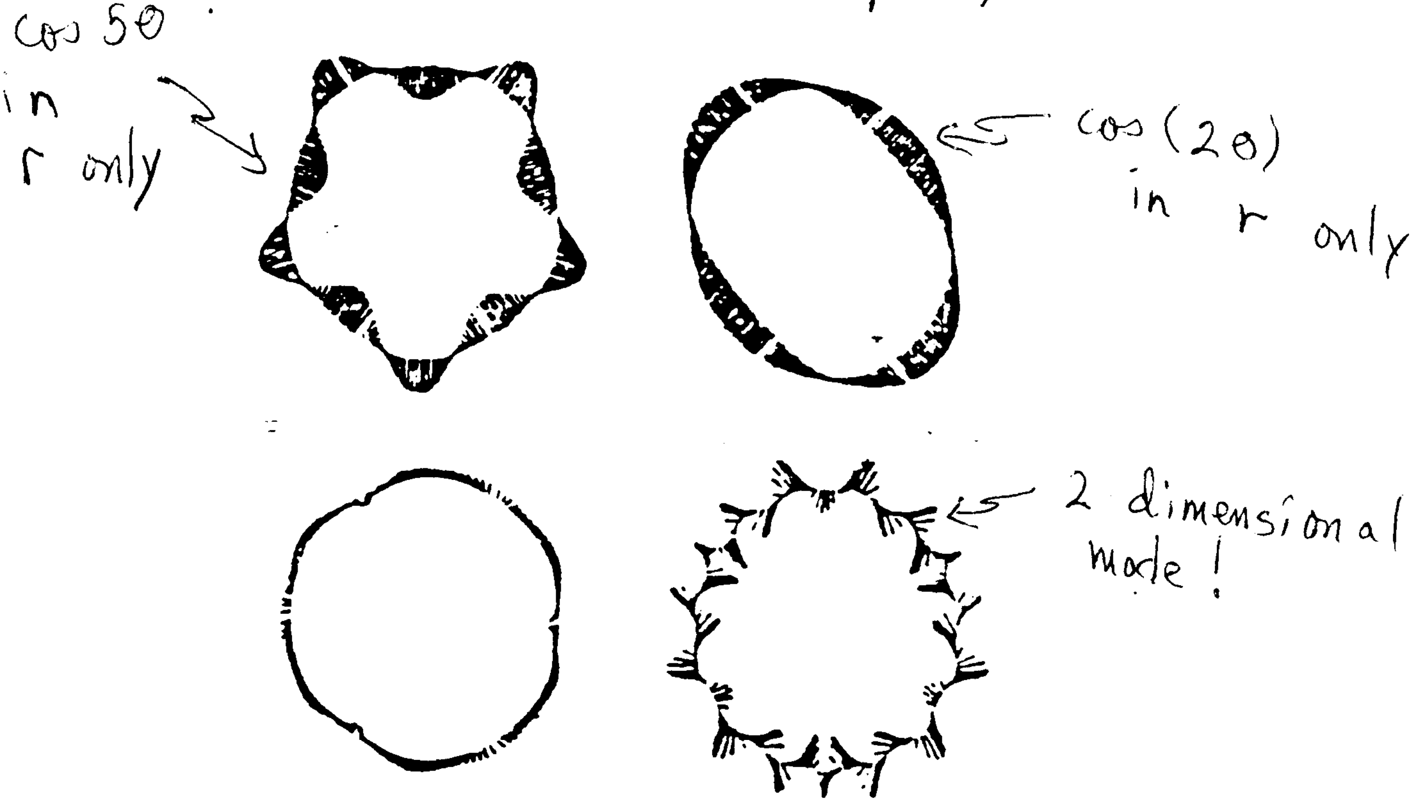


note: the quadrupole "position" was encoded by a K+E target on the floor placed by plummeting down from a fixture which referenced the grove in the lamination at the downstream holes in the "tie plate" (see fig below)

re 1 Survey variables: sagittas, Dk, and next nearest-neighbor chords, ak.



Michelotti analysis:
(fictitious examples)



ure 3 A few low order singular vectors. Many of these look much like pure Fourier harmonics, but others are markedly different.

low order modes can be induced by the measurements errors, or they can represent the true shape of the ring -

in Either case they DO NOT MATTER to machine performance!!

So subtract them out!!

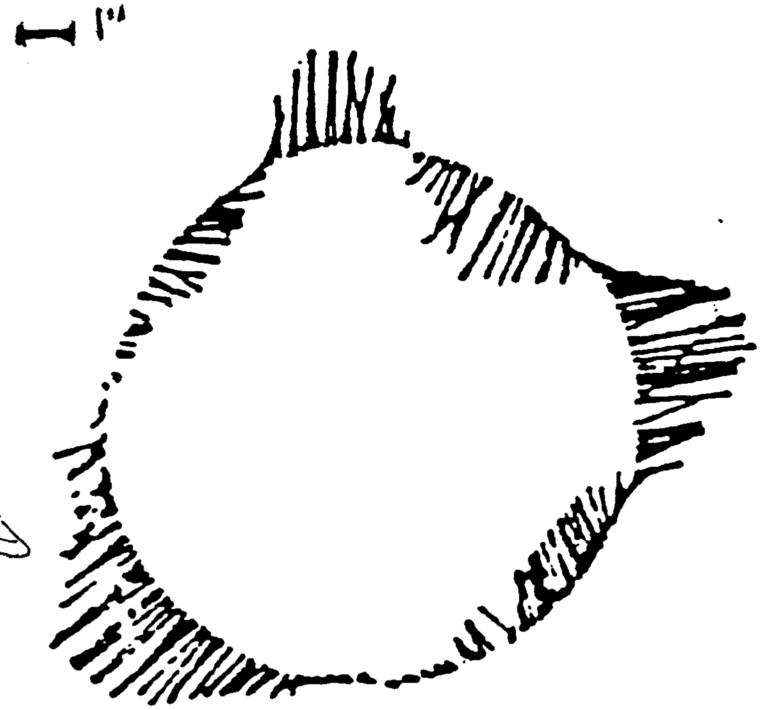
Michelotti

from our sagitta + length measurements:

Pseudoinverse solution

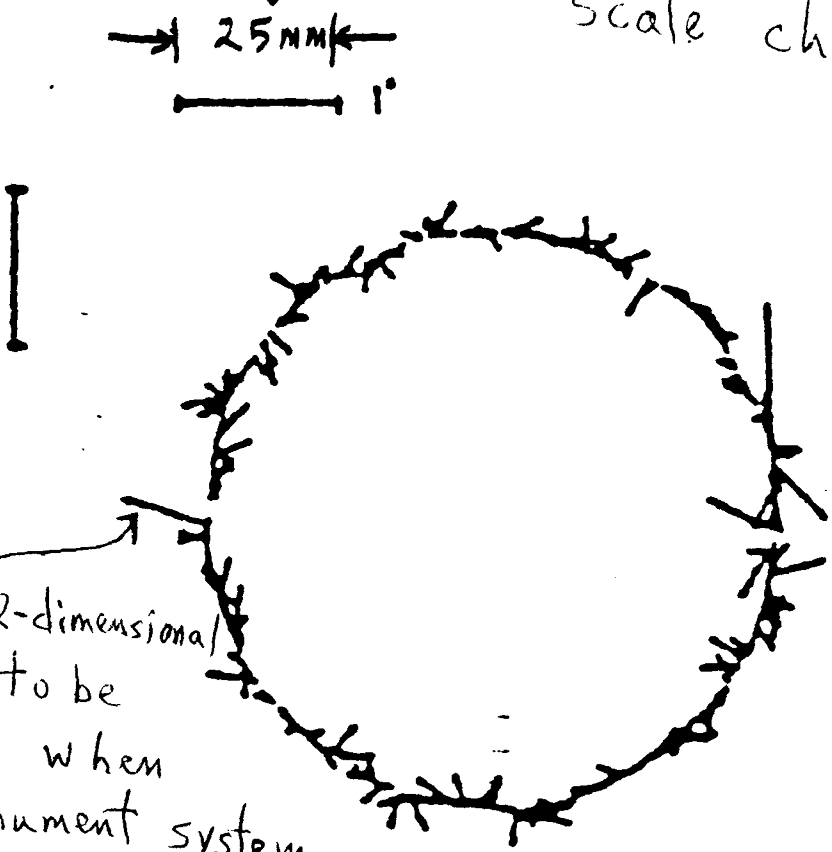
25mm {I

note strong $\cos 3\theta$ term



without suppression of low-order "modes", or harmonics.

note scale change



Solution after subtracting extra low order modes

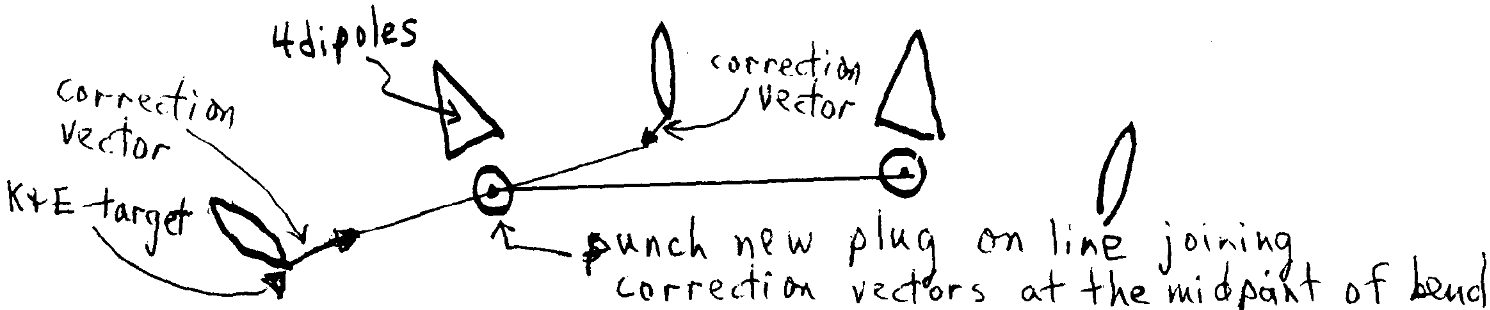
this is the 2-dimensional "correction" vector to be applied to this quad when setting the new monument system

(a)

after suppression of ≃ 10 low-order "harmonics" such as previous picture

Horiz plane (l, r) monument system

Offset brass plugs at each bend point



1) lines ∥ quad or "straight section"
2) Offset to beam in all straights <u>always</u> = 26.525" (why?)
3) only $\underline{\underline{5}}$ offset numbers to remember
4) <u>But</u>: 2 plugs at "missing magnet" locations

<u>Installation</u>

– Use Michelotti "correction vectors" to give l_{LEFT}, l_{RIGHT}, offset of new plug relative to nearest 2 quads
– redundancy in l
– no redundancy in r ⟹ fishline (nylon) fast check done ($\sigma_{r_{fish}}$ = 0,56 mm !) (very good!)

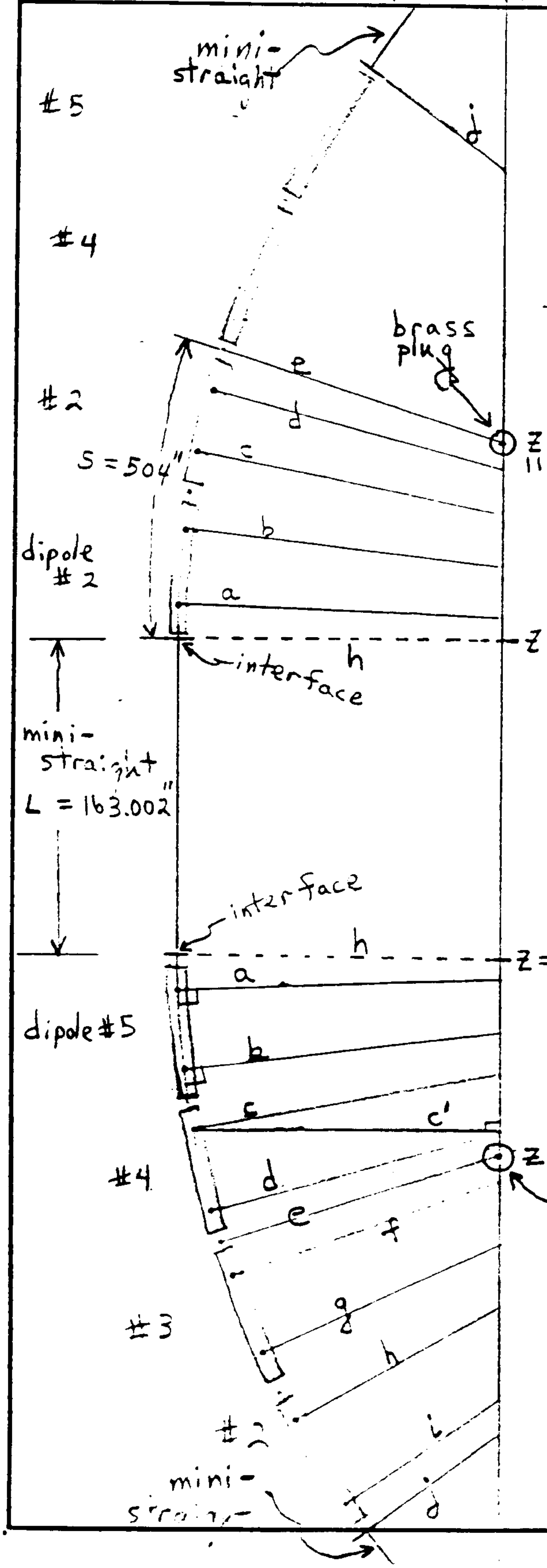
"Murphy line" hand-stretched nylon line on floor, "snapped" upward several times to remove snags in the fl

offset

FERMILAB **ENGINEERING NOTE**

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
Saver	Doubler		1

SUBJECT	NAME
Doubler orbit offsets from brass plug line at magnet supports—NORMAL CELL	C. T. Murphy
	DATE 9/4/81
	REVISION DATE



name	radial offset	perpendicular offset
mini-straight	h = 26.525	
#5 DS, #2 US	a = 26.476	a' = 26.476"
#5 US, #2 DS	b = 25.900	b' = 25.900
#4 DS, #3 US	c = 25.008	c' = 25.007
#4 US, #3 DS	d = 23.280	d' = 23.278
mid point	e = 22.437	e' = 22.434
for use in "backward" shot	f = 21.496	f' = 21.492
	g = 18.615	g' = 18.611
	h = 15.937	h' = 15.932
	i = 11.903	i' = 11.898
begin next mini-straight	j = 10.166	j' = 10.161

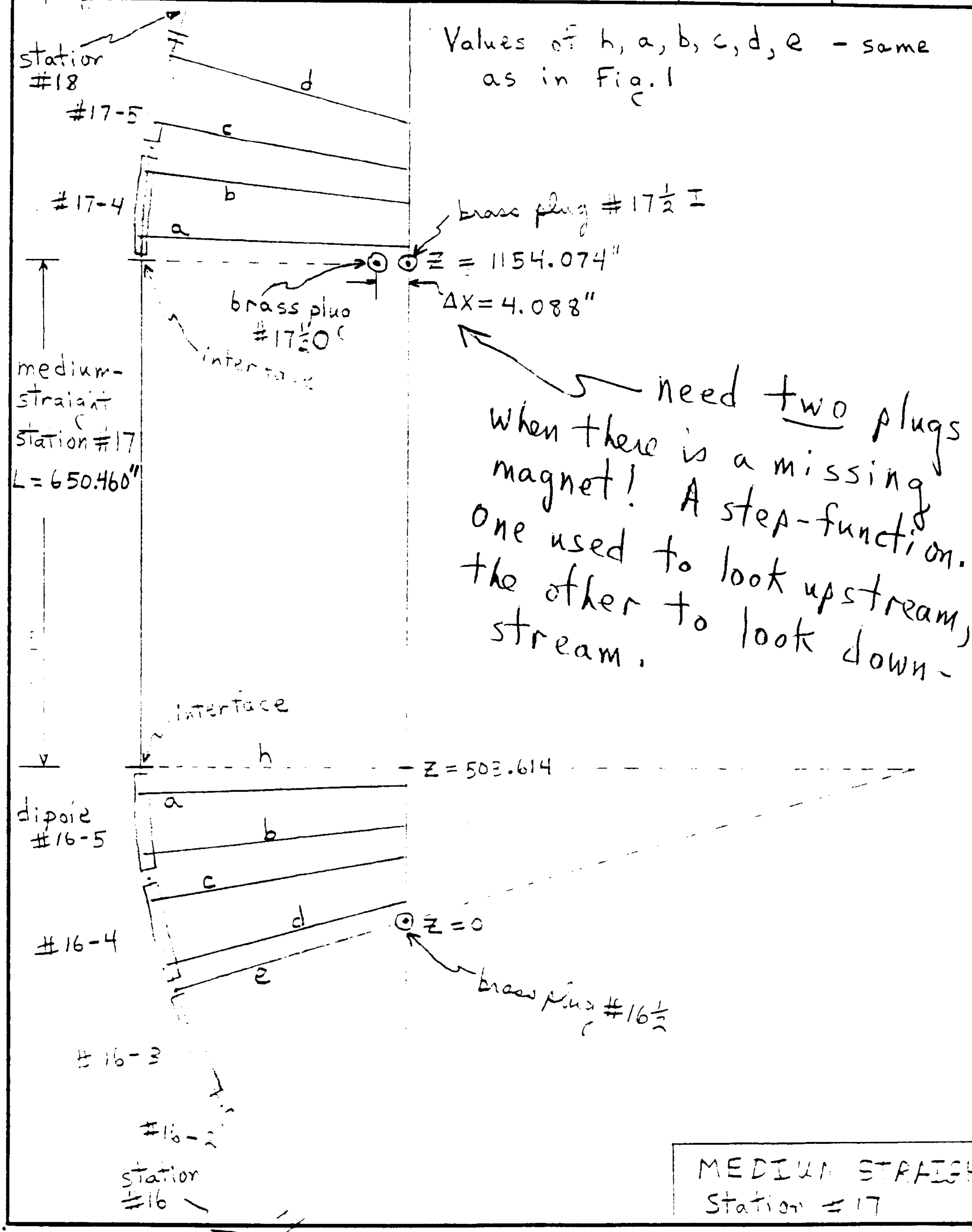
Craig Moore has the TM of which this is a part

Distance of support point to nearest interface = 55"

NORMAL CELL

FERMILAB ENGINEERING NOTE	SECTION	PROJECT	SERIAL-CATEGORY	PAGE
	Saver	Doubler		2

SUBJECT	NAME	
Doubler orbit offsets from brass plug line at magnet supports - STATION #17	C.T. Murphy	
	DATE 9/4/81	REVISION DATE



MEDIUM STRAIGHT
Station #17

$$\langle\theta_{corr}\rangle_H = \left[m \frac{\bar{\beta}}{\beta_{max}} \langle\Delta\theta_{dipole}\rangle^2 + \frac{(\Delta Q)^2_{rms}}{F^2} \left(\frac{\beta_{max} + \beta_{min}}{\beta_{max}} \right) \right]^{\frac{1}{2}}$$

where $F = 1/K\ell_Q$ is the focal length in meters

and $\Delta\theta_{dipole} = \bar{\theta}_{dipole} \left(\frac{\Delta B}{B}\right)_{rms} = \frac{2\pi}{N_B} \left(\frac{\Delta B}{B}\right)_{rms}$

$m = 8 =$ # dipoles between H correctors

$\frac{\bar{\beta}}{\beta_{max}} \approx 0.7$ typical machine

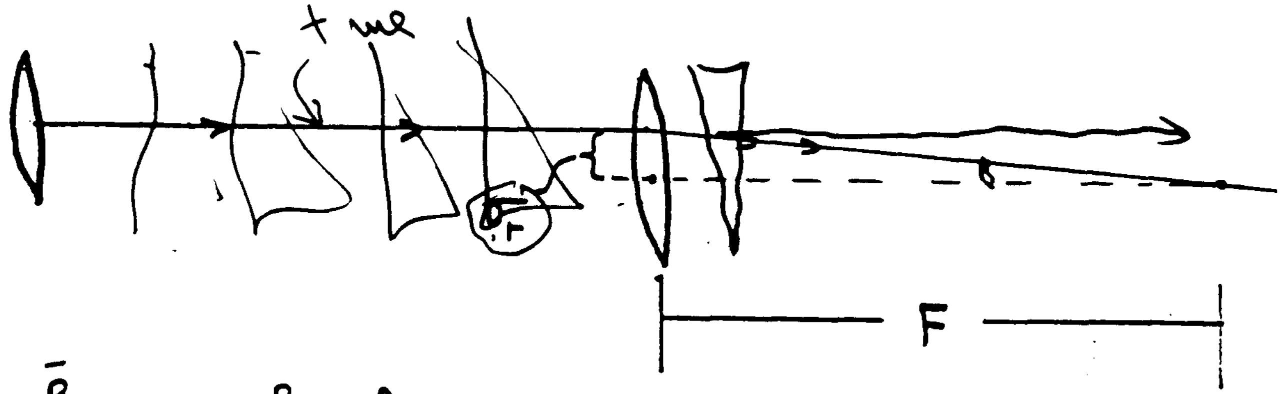
$\Delta Q =$ error in H-coord of quad (monument error + setting error)

$$\langle\theta_{corr}\rangle_V = \left[m \frac{\bar{\beta}}{\beta_{max}} \langle\Delta\phi_{roll}\rangle^2 + \frac{(\Delta Q)^2_{rms}}{F^2} \left(\frac{\beta_{max} + \beta_{min}}{\beta_{max}} \right) \right]^{\frac{1}{2}}$$

where $\Delta\phi_{roll} = \bar{\theta}_{dipole} (\Delta\phi)_{rms} = \frac{2\pi}{N_B} (\Delta\phi)_{rms}$

"roll"

$$\langle\theta_{corr}\rangle_H \simeq \left[m \frac{\bar{\beta}}{\beta_{max}} \langle\Delta\theta_{dipole}\rangle^2 + \frac{(\sigma_r)^2_{rms}}{F^2} \left(\frac{\beta_{max} + \beta_{min}}{\beta_{max}} \right) \right]^{1/2}$$



$$\frac{\bar{\beta}}{\beta_{max}} \simeq \frac{1}{2} \frac{\beta_{max}+\beta_{min}}{\beta_{max}} \simeq 0{,}7 \quad \text{typical machine}$$

m = 8 SPS, Tevatron

= ? LEP (depends what one calls "one magnet"

H $\frac{\Delta B}{B_0}$

V roll $\angle\phi_{roll}$

<u>Alignment of elements</u> (Moore)

require $\Delta z, \Delta r < 0{,}25$ mm

- relative to monuments

dipole roll $< 0{,}18$ mrad

<u>Final smoothing</u>: not allowed! (History repeats)

<u>But</u>: closed orbit at 512 GeV without moving quads (but helped by correction dipoles)

times: correct injection – 24 hrs

circle 1/3 ring – 1 pulse !
(no correctors)

circle 2/3 ring – 10 hrs

<u>How well did we do?</u> (see formula)

<u>Horiz</u>: $\sigma_r \simeq 0{,}56$ mm <u>est.</u> $\Rightarrow \langle \Theta_{corr} \rangle =$ 24 μrad

magnet set error plus monument error

$\frac{\Delta B}{B} = 10^{-3}$ $\longrightarrow$ + 18 "

expect: 30 (addition in quadrature)

rms corrector angle $\longrightarrow$ **observed**: 35

<u>Vert.</u> $\sigma_z \simeq 0{,}15$ <u>est.</u> entropy

$= 0{,}30$ observed, 1 yr. $\Rightarrow \langle \Theta_{corr} \rangle =$ 12

$\Delta\Phi_{roll} = 0{,}28$ mrad $\longrightarrow$ + 5

expect: 13

rms corrector angle

A comparison of machines

"Design"

Quantity	Tevatron 1000 GeV	SSC 20,000		LEP 100	BEPC (Beijing)
$\left(\frac{\Delta B}{B}\right)_{rms}$	10×10^{-4}	3×10^{-4}		5	3,5
$\Delta\phi_{roll\ rms}$	0,5 mrad (Design)	0,5 mrad		0,24	0,2
σ_r, σ_z	0,63 mm	0,8 mm		0,14	0,2
$\langle\theta_{corr}\rangle, r$	32 μrad	7,5 μrad	at every Q	9,2 (?)	88
$\langle\theta_{corr}\rangle, z$	27	7,74		5,7 (?)	75
$\theta_{corr, Max}$	142	47,7	occurs at only $\approx$ 2/3 of Quads	87 r 52 v	1110 r 1338 z
"safety factor"	4.7	6,3		~~9.1, 9.4~~ $\underbrace{5-6-7}$ Mayoud guess	12 r 18 z

$\equiv \frac{max}{\langle\theta_c\rangle}$

defined to be equal to

"Alignment Decay", or "Ground motion"

<u>rms alignment deviation as function of time</u>

<u>Fermilab</u>, Tevatron

$\sigma_z \approx 0.15$ mm 1982-3

$\sigma_z = 0.30$ mm 1984

$\sigma_z \simeq 0.75$ mm 1986

<u>CERN</u>, SPS

$\sigma_r = 0.08$ mm as set

$\sigma_r = 0.26$ 9 yrs later

$\sigma_z \leq 0.1$ mm set

$\sigma_z \approx 0.3$ mm 4 yrs later

- realigned 83 quads

$\sigma_z = 0.20$ (of $\simeq 200$)

$\sigma_z = 0.24$ 5 yrs later

4 July, 1986

To: SSC Alignment Afficianados
From: Thornton Murphy CGM
Subject: SPS Movement

Some of you expressed an interest in finding out what CERN knows about gradual misalignment of the SPS over long time periods as a result of ground motion or other effects. Mayoud has given me a few numbers which he is willing to let me pass on. Recall that the SPS is set in molasse, or "bedrock", about 50 m below the surface of the earth.

In the horizontal plane the original ("as set") σ_r was 0.08 mm. The definition of σ_r is the standard deviation of the offset of a quadrupole from the line joining its nearest neighbors, minus the theoretical value of course. After nine years, this σ_r was found to have grown to 0.26 mm.

In the vertical direction, the situation is not so clear, because a dominant effect was the sinking of the concrete under the heavily loaded third (or "unique" as they call it here) jack of the large quadrupoles. The definition of σ_z is the standard deviation of elevation differences between adjacent quadrupoles, and the original value ("as set") was less than 0.1 mm in 1976. In 1980, they had to move 83 of the 216 quads by an rms value of 0.46 mm to bring σ_z back to an acceptable value of 0.20 mm. (Thus σ_z for all 216 quads before moving 83 of them must have been around 0.30 mm.) In January 1985, they measured the elevations of all the quads again and found σ_z = 0.24 mm. The mean value of the difference of elevation between the two ends of each quadrupole was 0.15 mm, a measure of the sinking of the concrete under the heavily loaded third jack over five years time.